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EFFECTS OF NUCLEAR RADIATION ON A HIGH-RELIABILITY SILICON POWER DIODE III - Junction Capacitance

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16. Abstract The effects of nuclear radiation on the junction capacitance of a 35 A, 600 PIV n ⁺ -p-p ⁺ power diode was determined for fast neutron fluences up to 4.6×10^{13} neutrons/cm ² . Capacitance changes ranging from a small decrease to as much as 50 percent increase were found for small reverse biases. These changes were probably due to channel formation. At large reverse biases, the junction capacitance remained essentially unchanged with radiation.			
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EFFECTS OF NUCLEAR RADIATION ON A HIGH-RELIABILITY

SILICON POWER DIODE

III - JUNCTION CAPACITANCE

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Lewis Research Center

SUMMARY

One hundred "high-reliability" silicon power diodes were irradiated, in different operating modes and at different temperatures, at a neutron fluence 0.1 MeV and above of 5×10^{13} neutrons per square centimeter and a gamma dose of 5×10^7 rads (C). The junction capacitance for most diodes increased with radiation, with changes at small reverse biases of up to 50 percent. Capacitance changes ΔC at large reverse biases were very small. The change in capacitance with radiation fell into two groups ($\Delta C = 50$ to 150 pF and $\Delta C = 450$ to 550 pF) at zero and low values of bias. The reason for this grouping was not determined.

Comparison of a set of diodes irradiated at a nominal 60° C with another set irradiated at a nominal 120° C showed nearly the same average capacitance change, although individual diodes varied widely. Similarly irradiation in different operating modes (reverse bias, ac, forward bias, dc) had little effect on capacitance changes.

The "built in" or diffusion voltage did not change appreciably with radiation.

INTRODUCTION

The junction (depletion region) capacitance associated with a silicon p-n junction, as a device, may or may not be an important parameter depending upon the intended circuit application. If the operating frequencies are relatively low and the transient response is not a stringent requirement, the capacitance is most likely not an important parameter. However, if fast switching times are required, then the junction capacitance C does become important. In either case, the value of the junction capacitance is very

useful in examining other properties such as depletion region width and built in voltages, and in calculating generation-recombination currents in the reverse bias mode.

This report will describe measurements of the effects of nuclear radiation on the junction capacitance of a $n^+ - p - p^+$ diode. The effects of radiation on other design characteristics have been described earlier (refs. 1 and 2).

DESCRIPTION OF DIODES TESTED

The diode investigated was an S1N1189. The prefix "S" in the part number indicates that the diode passed the NASA Marshall Space Flight Center screening and performance specification (ref. 3). The silicon chip configuration is shown in figure 1 and

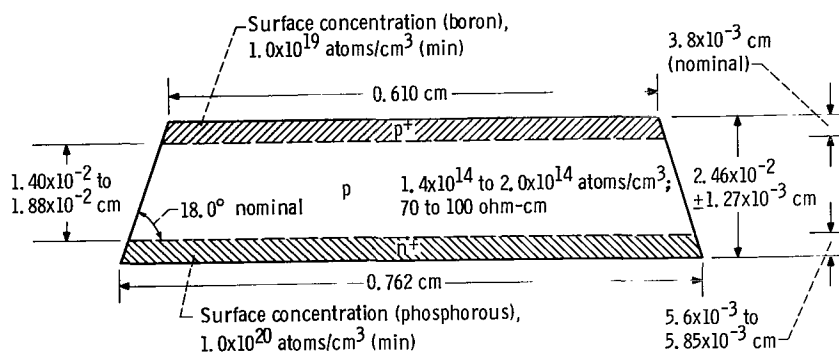


Figure 1. - Silicon chip configuration of S1N1189. (Drawing not to scale.)

has an $n^+ - p - p^+$ -type junction prepared by a double-diffusion process. The base region p-material is doped to 1.4×10^{14} to 2.0×10^{14} boron atoms per cubic centimeter. The p^+ -region has a surface doping concentration of 1.0×10^{19} boron atoms per cubic centimeter (minimum). The nominal depth of the $p - p^+$ junction is 38 micrometers. The n^+ -region has a surface doping concentration of 1.0×10^{20} phosphorous atoms per cubic centimeter (minimum) with a nominal $n^+ - p$ junction depth of 57 micrometers. The chip is circular with sides beveled to a nominal 18° slope, which lowers the electric field at the surface. The beveled sides are coated with a silicone rubber to form a passivation layer on the surface. The nominal diameter of the chip on the p^+ -side is 0.61 centimeter and is 0.76 centimeter on the n^+ -side. The overall thickness of the chip is approximately 2.54×10^{-2} centimeter.

SYMBOLS

a	doping gradient, atoms/cm ⁴
C	junction capacitance, pF
ΔC	junction capacitance change, pF
K'_N	damage constant, atoms/(neutron)(cm)
k	dielectric constant for silicon
N	effective base doping level after irradiation
ΔN	change in effective base doping level with irradiation
N_D	base doping level, atoms/cm ³
N_S	surface concentration, atoms/cm ³
q	charge on electron, C
R_1	resistance, ohms
V	voltage, V
V_B	built in or diffusion voltage, V
W	junction width as determined from capacitance measurements
ϵ_0	permittivity of free space, F/cm
ϕ	fast neutron fluence, neutrons/cm ²

DESCRIPTION OF IRRADIATION

The two factors expected to be most important in modifying the damage due to nuclear radiation in an operating space power system are the operating temperature and current. Therefore, the test described hereinafter was designed to measure the effect of these two parameters.

The irradiation testing of the diodes actually consisted of two separate tests. In each, 50 diodes were irradiated simultaneously in the reactor under similar conditions, with the important difference being the temperature at which the two sets of diodes were irradiated. Each test set of 50 diodes was divided into groups according to the operating modes given in table I. The operating currents and voltages chosen were substantially below the diode rating (10-A current and 150-V reverse voltage, as contrasted to ratings of 35 A and 500 V). This derating is typical of that used for high-reliability applications.

All diodes in each test were operated in the modes (table I) during irradiation except

TABLE I. - DIODE GROUPING FOR EACH TEST BY OPERATING
MODES WITH AVERAGE INITIAL AND FINAL
IRRADIATION TEMPERATURES

Group	Diodes per group	Operating mode	Set			
			I		II	
			Neutron fluence, neutrons/cm ²			
			4.6×10 ¹³		4.0×10 ¹³	
			Average temperature, °C			
			Initial	Final	Initial	Final
A	10	Forward current, 10 A dc	48.5	60	106	125
B	10	Reverse biased, 100 V dc	38	43	103	102
C	30	ac rectification; average forward current, 10 A; peak reverse voltage, 150 V	50.5	66	99	124
Nominal temperatures, °C			----	60	---	120

when measurements were taken. The irradiation of each test set proceeded for two reactor cycles, the nominal reactor cycle being 10 days at rated power, depending on the reactor power scheduling. The average temperatures of the diodes during irradiation (table I) were different for the three operating groups because one coolant line served all the diodes on each test plate, and each diode was its own heat source. For example, the reverse-biased group generated less heat than the forward-biased group and therefore operated at lower temperatures. Table I also includes the change in average operating temperatures as each test progressed. As used in this report, designated nominal temperatures represent the average final temperature.

The first set of diodes (test I, 60° C nominal) received a fast-neutron (≥ 0.1 MeV) fluence of $4.6 \pm 1.5 \times 10^{13}$ neutrons per square centimeter, and the second set of diodes (test II, 120° C nominal) received $4.9 \pm 1.6 \times 10^{13}$ neutrons per square centimeter. The gamma dosage for each set of diodes was $3.2 \pm 0.6 \times 10^7$ rads (C).

The methods for determining the fast-neutron flux and gamma dosage and the conditions for which a calculated flux can be obtained are described in references 4 and 5.

METHOD USED FOR CAPACITANCE MEASUREMENTS

The diode junction capacitance was measured on all 100 diodes used in both tests I and II. The measurements were made before and after irradiation using a bridge circuit arrangement as shown in figure 2. The frequency of the applied voltage was 10 kilohertz and the peak-to-peak amplitude of the voltage across the diode was 0.080 volt. The reverse-bias voltage was applied through a 100 K ohm resistor R_1 as shown in figure 2. Measurements were made on all diodes before and after irradiation at

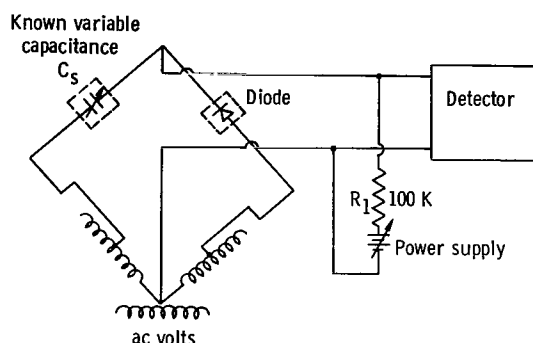


Figure 2. - Bridge circuit for measuring junction capacitance.

reverse-bias values of 0, 7.5, 94, and 300 volts. Capacitance was also measured at bias voltage values down to 0.5 millivolt on a few samples. To check the repeatability of the capacitance measurements, values were determined before and after irradiation on control diodes which had not been irradiated. The repeatability was found to be within 1 percent.

EXPERIMENTAL RESULTS

Variation of Junction Capacitance with Voltage Before Irradiation

Figure 3 shows the variation of capacitance with reverse-bias voltage V from 10 millivolts to 300 volts before irradiation. The four diodes shown are representative of the entire group. There is a smooth variation in slope from a voltage dependence of $(V - V_B)^{-1/3}$ at low applied voltages to $(V - V_B)^{-1/2}$ at large applied voltages, where V_B is the "built in" or diffusion voltage. See also figure 4 where C is plotted against $V - V_B$ for a typical diode. Here the two voltage regions are easily seen. This type of capacitance change with applied voltage for a diffused junction diode has been treated

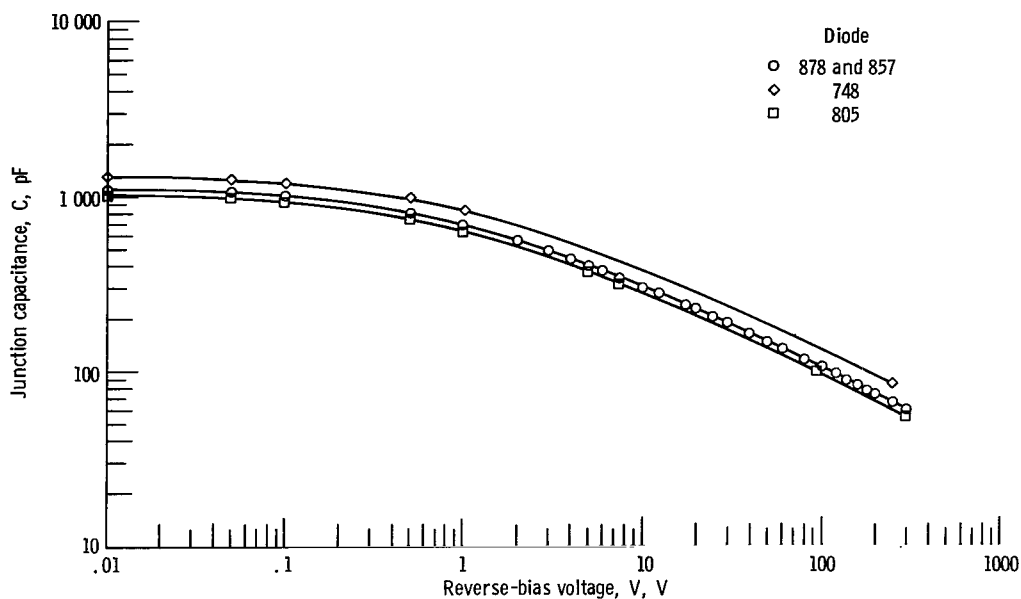


Figure 3. - Junction capacitance as a function of reverse-bias voltage V before irradiation.

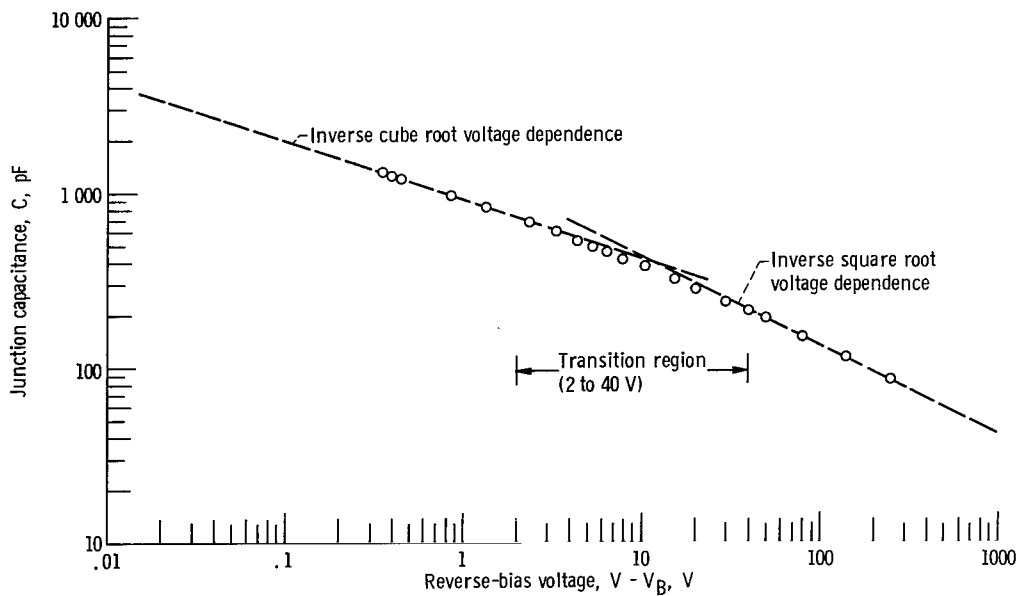


Figure 4. - Junction capacitance as a function of reverse-bias voltage $V - V_B$.

in detail by Lawrence and Warner (ref. 6) and by Myers and Been (ref. 7) and is as expected. V_B was determined to be 0.35 volt as shown in appendix A. It should be noted that, for reverse biases, V is negative, so that the quantity plotted in figure 4 on the abscissa is numerically $|V - 0.35|$.

Variation of Capacitance with Voltage After Irradiation

Figures 5 and 6 show log-log plots of the junction capacitances against voltages of two typical diodes before and after they have been irradiated. These two diodes show an approximate 30 to 50 percent increase in junction capacitance with radiation at very low reverse bias voltage but considerably less increase at higher reverse voltages.

The 100 diodes irradiated were operated during irradiation in the three operating modes as shown in table I, namely, 10 amperes dc forward current, 100 volts dc reverse bias, and ac rectification with 10 amperes average forward current and 150 volts peak reverse voltage. The average results, considering the effects of these operating modes on radiation damage are shown in figures 7 to 10 for the voltage range 7.5 to 300 volts. The curves in figures 7 and 9 for unirradiated diodes are not identical. Their variation from one another is a measure of the variation of the average of one group from the average of another group. The effect of operating temperature on capacitance changes with radiation was minimal. Compare figures 8 and 10.

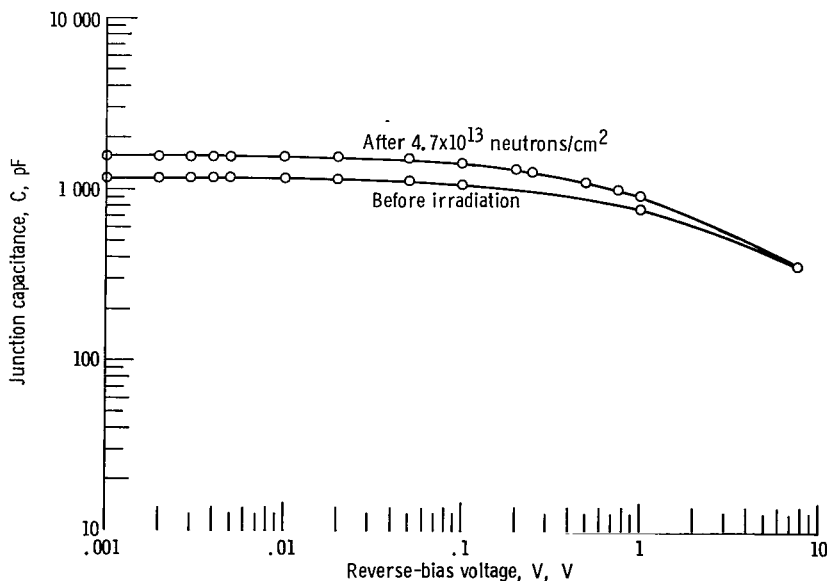


Figure 5. - Junction capacitance as a function of reverse-bias voltage for diode 879.

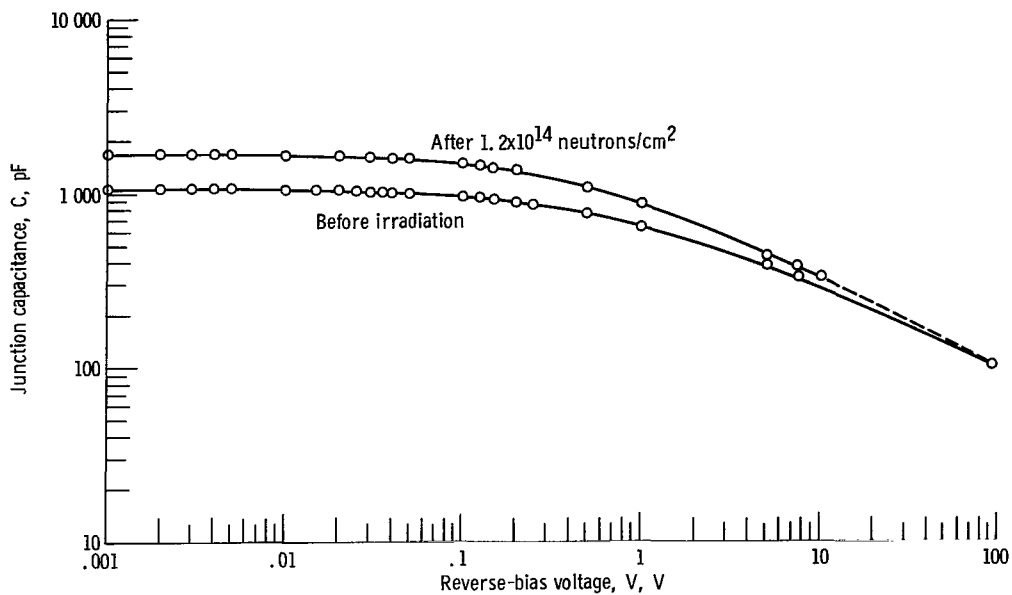


Figure 6. - Junction capacitance as a function of reverse-bias voltage for diode 805.

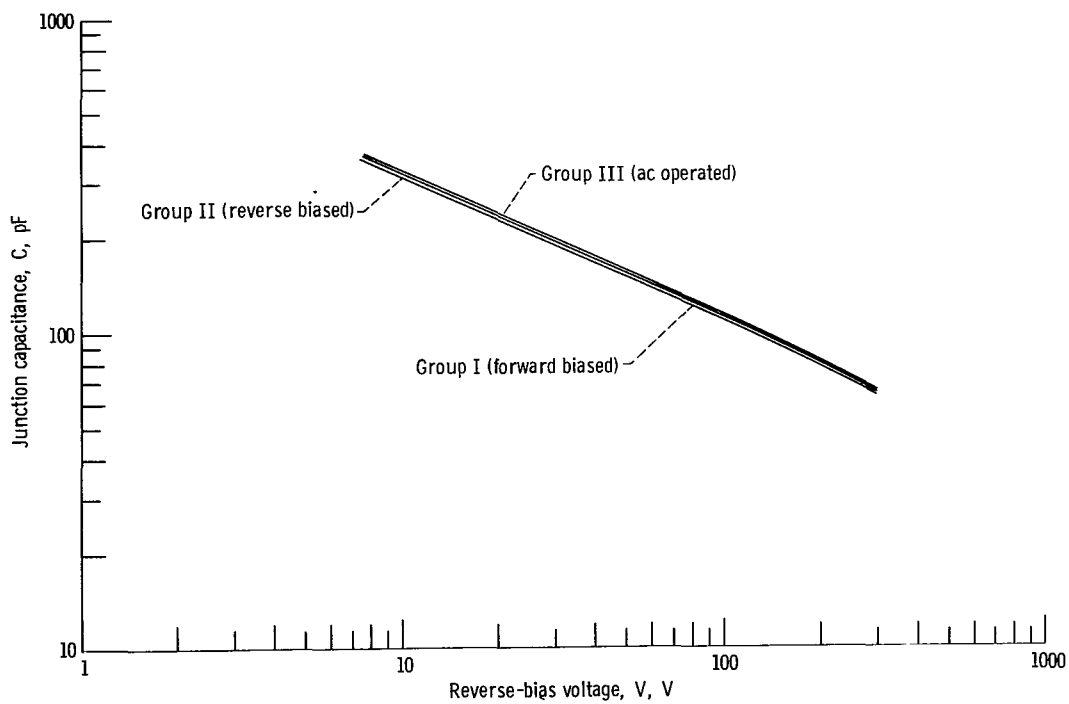


Figure 7. - Average junction capacitance as a function of reverse-bias voltage by operating modes before irradiation. Test I.

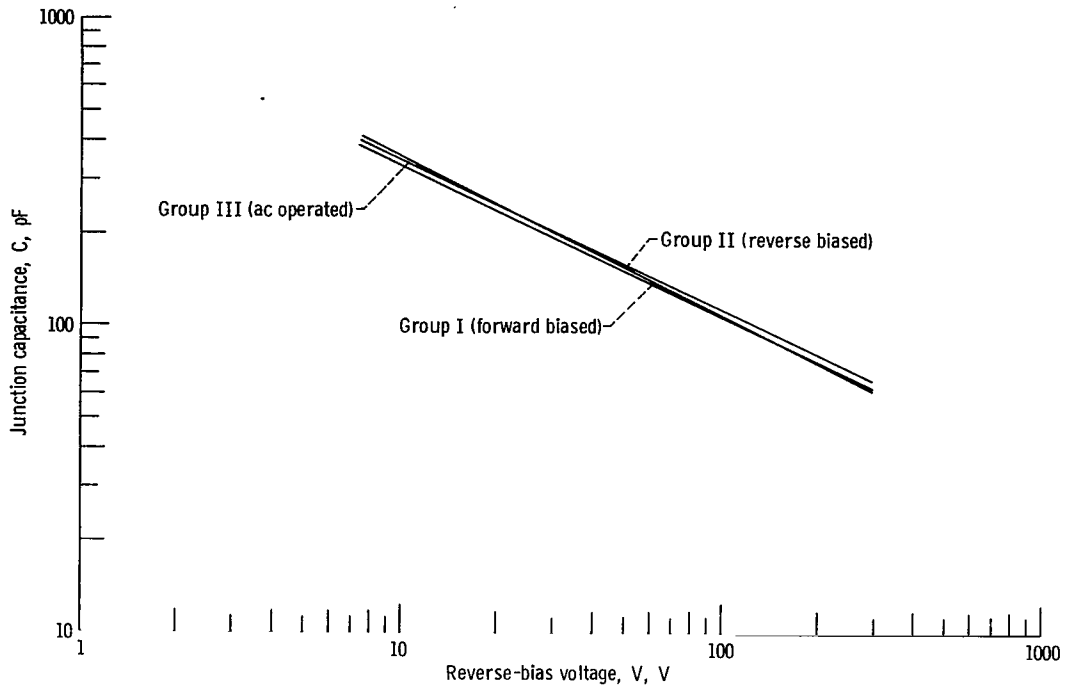


Figure 8. - Average junction capacitance as a function of reverse-bias voltage by operating modes after irradiation. Test I.

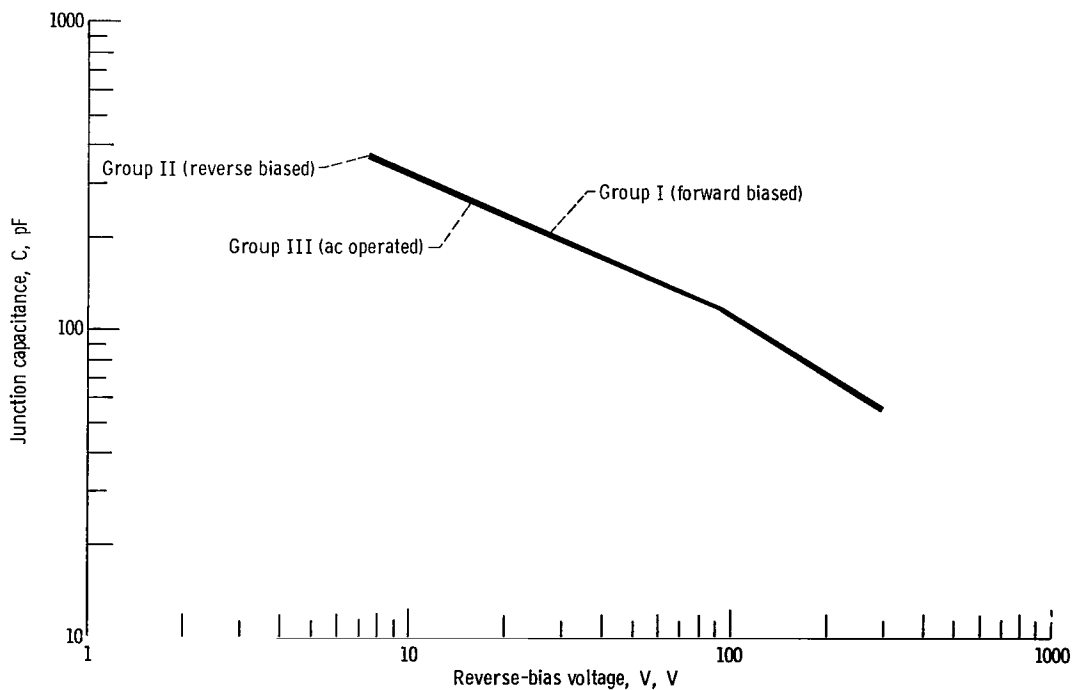


Figure 9. - Average junction capacitance as a function of reverse bias voltage by operating modes before irradiation. Test II.

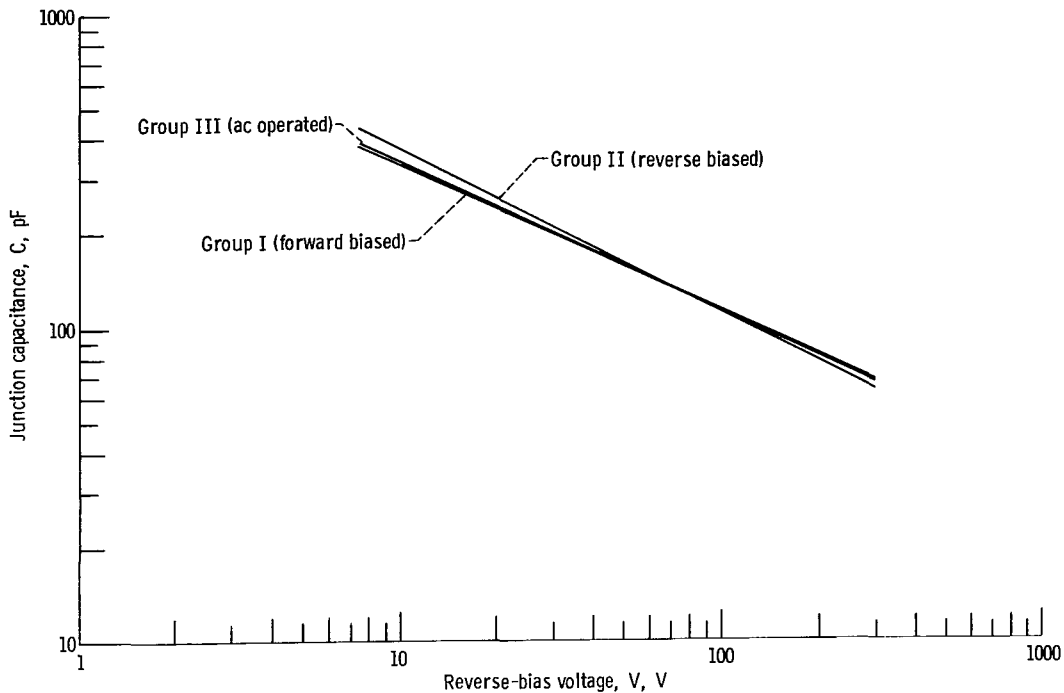


Figure 10. - Average junction capacitance as a function of reverse-bias voltage by operating modes after irradiation. Test II.

There appears to be a somewhat larger capacitance change for the reverse-bias operating mode at the lower bias voltages. However, this variation of average capacitance with operating mode is less than the variations from one diode to another and therefore cannot be considered conclusive.

The operating mode, then, does not have a significant effect on the capacitance with irradiation. Furthermore, it was found that, regardless of operating mode, the change of junction capacitance fell into a high group and a low group. The changes in capacitance at zero bias due to irradiation are shown in figures 11 and 12. The division into groups is more pronounced in test 1, figure 11, than in test 2, figure 12, although the division can be seen in both cases. Each block represents a diode with the symbol in the block representing the operational mode during irradiation.

The changes with radiation are possible due to the formation of surface channels but the grouping is not understood. Relatively large capacitance changes can be caused by small channel areas, if the channel thickness is small. For example, a channel area of 0.01 square centimeter combined with a channel thickness of 0.2 to 0.5 micrometer could explain the observed increase in zero bias junction capacitance with radiation. (These numbers have no experimental basis and are given only by way of example to show that reasonable channel areas and thicknesses could produce capacitance changes of the magnitude actually observed.) Lindmayer and Wrigley (ref. 8) speak of the

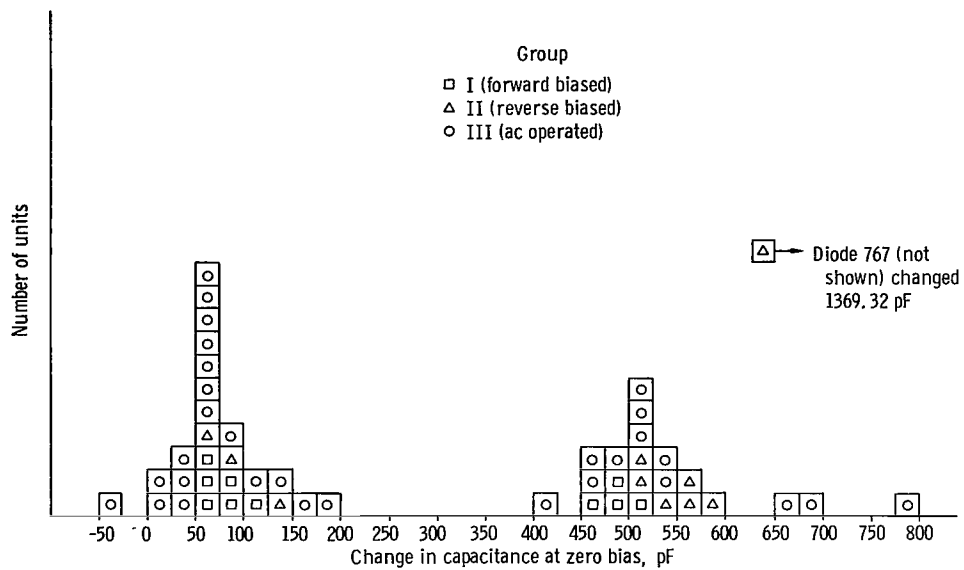


Figure 11. - Graph showing distribution of change in capacitance with irradiation. Test I.

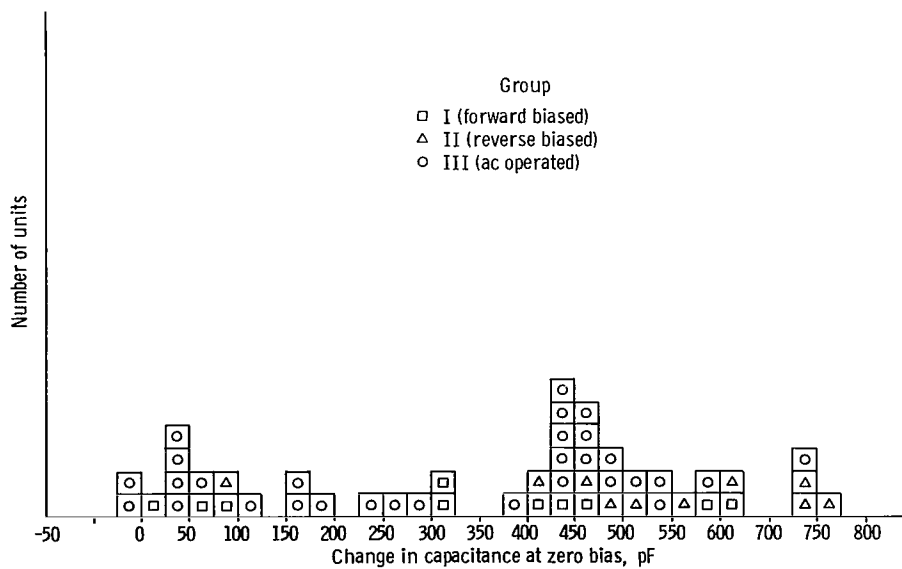


Figure 12. - Graph showing distribution of change in capacitance with irradiation. Test II.

"pinching off" of channels at higher voltages, with the effective added junction capacitance becoming small or zero, which could explain the lack of increase of capacitance with radiation at higher voltages.

An attempt was made to determine channel area and thickness quantitatively from the experimental data, using theoretical expressions for capacitance and current as a function of voltage. Equations were written for capacitance and current at different voltages, and before and after irradiation. The resulting equations were solved for the depletion region widths at the different voltages, the diffusion current constant, the recombination generation current constant, the leakage resistance, the radiation damage constant, and the channel areas and thicknesses at the different applied voltages. This approach for obtaining the channel areas and widths, while attractive in principle was unsatisfactory in practice. It was concluded that the mathematical model used was not good enough to allow the simultaneous solutions required. An attempt was also made to explain the experimental results in terms of a uniform distribution of charged donor or acceptor traps created in the space charge region by radiation damage. Using these space charge distortions, capacitance-voltage dependences were derived. Only the donor trap case predicted the observed increase in capacitance at low bias and the approach to the pre-irradiation values at high bias. However, the magnitude and the fall-off with bias of the capacitance change did not compare favorably with the experimental results.

Capacitance changes due to carrier removal (reduction of effective base doping level by neutron irradiation) were calculated (see appendix B). Results depended somewhat upon operating voltage, but were of the order of 1 to 2 percent. This change is small compared to changes due to other effects. It is possible that both channeling and compensation due to carrier removal were present (although carrier removal effects are small) since carrier removal causes a decrease in junction capacitance and channel formation causes an increase.

The diffusion or "built in" voltage V_B of the junction was determined by plotting $1/C^3$ against voltage. The value obtained, 0.35 volt, was in good agreement with that calculated from the doping ingredient. V_B did not change measurably with radiation. See appendix A for details.

CONCLUSIONS

One hundred "high-reliability" silicon power diodes were irradiated in two separate tests of fifty diodes each, in different temperature and operating modes. They were exposed to a fast neutron fluence (0.1 MeV and above) of 5×10^{13} neutrons per square centimeter and a gamma dose of 5×10^7 rads (C). The results of the junction capacitance measurements were:

1. The junction capacitance C for most diodes increased after irradiation, with changes at small reverse voltages of up to 50 percent.

2. The junction capacitance changes with radiation at large reverse voltages (100 V or more) were very small. This is consistent with channeling pinch off at high voltages and with carrier removal effects.

3. The diodes operated in the reverse-bias mode during irradiation had on the average somewhat more junction capacitance change ΔC than those irradiated while ac operated or forward biased. This effect was small compared to variations between individual diodes.

4. The change in zero bias junction capacitances with radiation seemed to fall into two well-defined groups. The lower group had a capacitance change with irradiation of 50 to 150 picofarads, while the second group had an increase of 450 to 550 picofarads. The reason for this grouping is not known. The groupings persist to higher voltages, although the magnitude of the changes decrease.

5. The effect of operating temperature on capacitance changes due to radiation was small.

6. The "built in" or diffusion voltage V_B as measured by the extrapolation of a $1/C^3$ against V plot to zero, was about 0.35 volt and changed very little with radiation. Measured and calculated values of V_B were in agreement.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 9, 1971,
120-60.

APPENDIX A

DETERMINATION OF THE DIFFUSION VOLTAGE V_B

The diffusion or "built in" voltage V_B was determined experimentally using the standard experimental method of plotting $1/C^3$ against V . See figure 13. V_B as determined by extrapolation of the $1/C^3$ plot was 0.35 ± 0.05 volt and seemed to be relatively unchanged by irradiation.

V_B was also calculated using the doping configuration as supplied by the manufacturer. The theory of Nuyts and Van Overstraeten (ref. 9) gives a relation between the doping gradient a and the diffusion voltage V_B that may be fitted by the following expression:

$$V_B = 0.080 \log_{10} a - 1.08 \text{ volts}$$

The value of the doping gradient a may be calculated from the surface concentration $N_s = 10^{20}$ atoms per cubic centimeter and base doping level of 1.4×10^{14} to 2×10^{14} atoms per cubic centimeter. For an exponential gradient, a is between 3×10^{17} and 5×10^{17} atoms per centimeter⁴; a complementary error function gradient gives values of a from about 5×10^{17} to 7×10^{17} atoms per cubic centimeter. These give values of V_B for the exponential gradient case of 0.32 to 0.34 volt and 0.34 to 0.35 volt for the complementary error function case. The complementary error function doping gradient is probably closest to the actual case. Agreement in this case is good between experimental and calculated values. Calculation of V_B from elementary theory, that is,

$$V_B = \frac{W^3 qa}{12k\epsilon_0}$$

where W is the junction width as determined from capacitance measurements, gives values generally that are considerably too high. This is to be expected since the simple theory omits the effects of carriers in the depletion region and also assumes an abrupt edge to the depletion region.

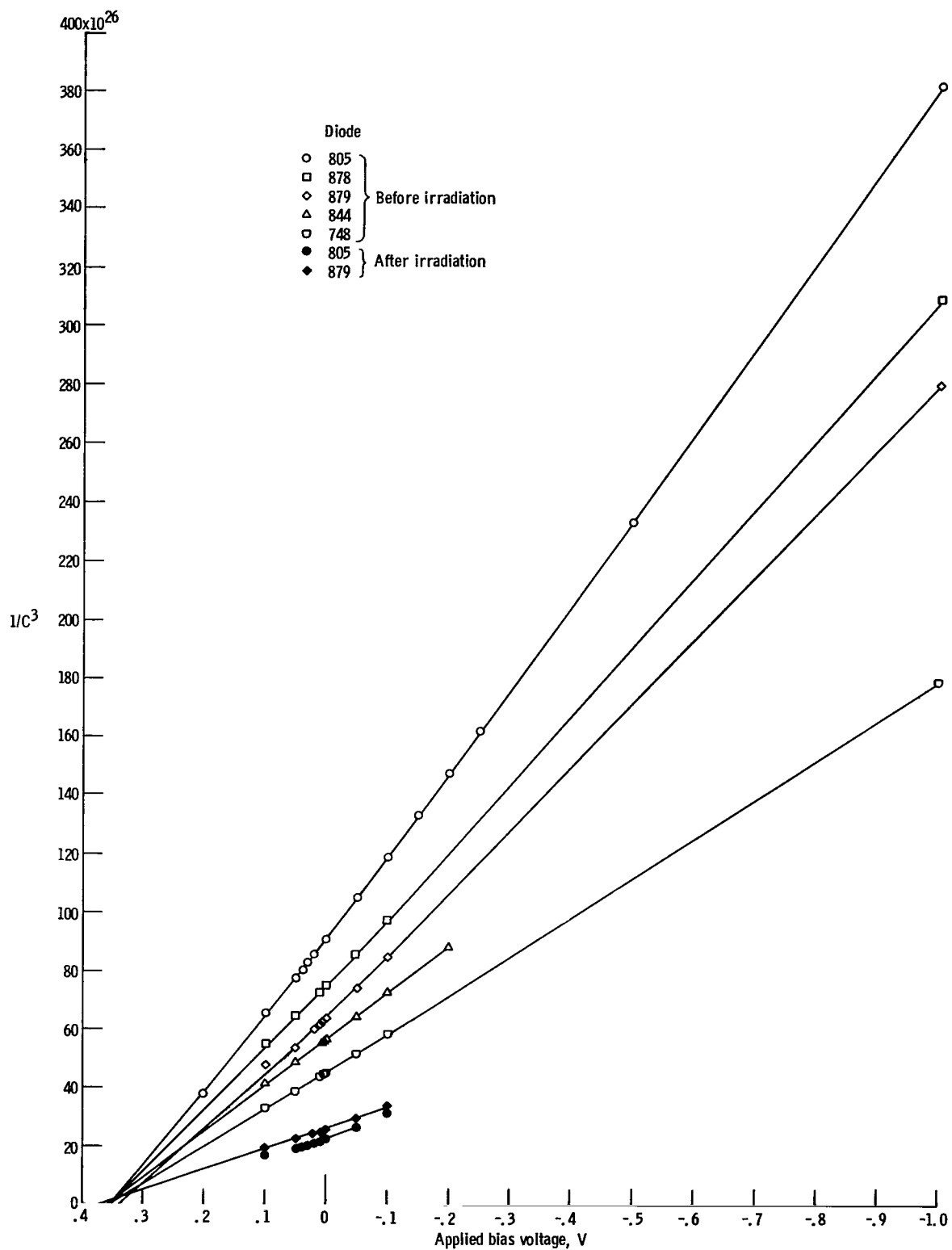


Figure 13. - Plot of $1/C^3$ as a function of applied bias voltage.

APPENDIX B

EFFECT OF CARRIER REMOVAL ON JUNCTION CAPACITANCE

Carrier removal theory may be used to predict the change in effective base doping level N and therefore the effective capacitance change with radiation. Ramsey and Emdee (ref. 10) plot K'_N against φ/N_D , where K'_N is a factor in the following equation:

$$N = N_D - K'_N \varphi$$

and

N effective base doping level after irradiation

N_D base doping level

φ fast neutron fluence, neutrons/cm²

For a fluence of 4.6×10^{13} neutrons per square centimeter and a base doping level N_D of 2×10^{14} atoms per cubic centimeter, K'_N is about 0.2 atoms per neutron centimeter and the relative change in N is 4 percent (where the relative change in N is $(N_D - N)/N_D = K'_N/N_D$). The capacitance varies as the cube root of the base doping level for low applied voltages, that is,

$$C = \left[\frac{k^2 \epsilon_o^2 q a}{12(V - V_B)} \right]^{1/3}$$

and as the square root of the effective base doping level for large applied voltages, that is,

$$C = \left(\frac{q k \epsilon_o N}{2V} \right)^{1/2}$$

At intermediate voltages the junction capacitance variation with N will be between the cube root and the square root dependence. By the theory of error, the relative change

in C then varies between

$$\frac{1}{3} \frac{\Delta N}{N} < \frac{|\Delta C|}{C} < \frac{1}{2} \frac{\Delta N}{N}$$

and since

$$\frac{\Delta N}{N} = \frac{N_D - N}{N_D} = 0.04$$

then

$$0.013 < \frac{|\Delta C|}{C} < 0.02$$

this change in capacitance (ΔC is negative) is thus at most 2 percent.

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